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Submarine Base, Groton, Conn.

REPORT NUMBER 545

ANALYSES OF A VARIETY OF VISUAL PROBLEMS ENCOUNTERED
DURING NAVAL OPERATIONS AT NIGHT

by

Jo Ann S. Kinney, S. M. Luria,

and

Donald O. Weitzman

Bureau of Medicine and Surgery, Navy Department
Research Work Unit MF12.524.004-9004.12

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COMMANDING OFFICER
Naval Submarine Medical Center

30 August 1968



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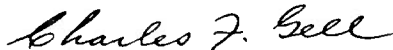
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SUBMARINE MEDICAL RESEARCH LABORATORY
NAVAL SUBMARINE MEDICAL CENTER REPORT NO. 545

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SUMMARY PAGE — REPORT No. 545

THE PROBLEM

Questions continually arise within the Navy as to the most effective lighting systems for various night-time operations. The answers to these questions depend upon a careful assessment of human visual functioning and capabilities in conjunction with the operational requirements.

FINDINGS

This paper presents empirical and theoretical analyses of a number of operational situations such as the lighting of aircraft hangar decks, problems in lighting for underway replenishment at sea, and consideration of various alternate lighting systems for night-time operations.

APPLICATION

These analyses, which have been presented elsewhere for the specific Naval problems, are compiled in order to assist others with similar problems.

ADMINISTRATIVE INFORMATION

This investigation was conducted as a part of Bureau of Medicine and Surgery Research Work Unit MF12.524.004-9004—Optimization of Special Senses in Submarine and Diving Operations, and in conjunction with Annapolis Division, Naval Ship Research and Development Center contracts under S4106, Task 11846 and Sub-project S4624-004, Task 11615

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ABSTRACT

This report is a compilation of six analyses of lighting problems encountered in Naval night-time operations, prepared in response to various requests from the Naval Ship Research and Development Command, Annapolis Division.

The first paper discusses the characteristics and functioning of the human eye—such as day and night sensitivity and acuity, dark adaptation and the physiological basis for red lighting—which must be taken into consideration in attacking an operational problem. The second paper discusses the same principles in greater detail and applies them to the specific problems of a darkened ship. The third paper discusses the advantages and disadvantages of red vs white lighting for ships at night in concrete terms for the problems of dark adaptation and operational efficiency aboard the ship and for the question of concealment of the ship from enemy lookouts. The fourth paper deals with the specific problem of the effects on night vision of using yellow or orange rather than red lighting. The fifth paper assesses the adequacy of current lighting specifications for fork-lift operators on the decks of supply ships. The final paper is an analysis of the results of a field study of mechanics' performance in repairing planes under three different conditions of illumination of red and white light.

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As indicated above, this report appears in six sections. It should be noted that each section has its own numbered illustrations, footnotes, and references.

ANALYSES OF A VARIETY OF VISUAL PROBLEMS ENCOUNTERED DURING NAVAL OPERATIONS AT NIGHT

INTRODUCTION

The use of the eyes at night is anything but a normal or routine response. It is not natural to have to wait for 15 to 30 minutes in order to see, to look away from what one wishes to see, or, after all the effort, to see so poorly. In fact the effective use of vision at night takes special training and special human factors design of instruments, equipment, and weapons.

The importance to the Armed Forces of night vision, or more generally, of human beings operating effectively at night, waxes and wanes over the years. The major impetus came in World War II when a vast body of knowledge on night vision was accumulated. Technological advances, particularly in electronic detection of the enemy, caused a decline in use of visual detection methods and in interest in techniques. Periodically, however, an immediate answer to the question of maximizing human effectiveness for some night-time operation is required. These usually arise during periods of active combat, as in Korea or in Vietnam, when problems usually considered to be routine suddenly become critical. Generally, the answer to these questions is available in the literature on human visual functioning, but it is not always easy to retrieve and apply.

During the past two years, we have assisted personnel at Naval Ship Research and Development Center (NSRDC) in a number of such problems; all of these involve the question of whether or not to utilize night vision and, if so, the most efficient means of achieving it.

The questions that have been asked and our answers to them have been compiled in this report in the hope that the information will be of help to others with similar operational problems. The report is presented in six sections, each with its own numbered figures, tables, footnotes, and references.

Section I

Characteristics of the Human Eye

The following summary of the character-

istics of human visual processes reviews the major characteristics that must be considered in application to any operational problem.

The eye contains two sets of photoreceptors, rods and cones, which differ in three pertinent respects: (1) The nerve fibers of the rods become much more interconnected as they proceed from the eye to the brain than do the nerve fibers of the cones. (2) The cones are found in greatest numbers near the center of the retina—indeed, at the very center there are only cones—and the rods are found mostly around the periphery of the retina. (3) The rods contain a special pigment called rhodopsin, which undergoes marked isomeric reorganization depending on whether or not it is exposed to light.

The results of these characteristics are that: (1) The rods become functionally much more sensitive to dim light than do the cones, but they are at the same time much less able to discriminate fine detail. This means, in turn, that: (2) The center of the eye, where the image of what we are looking directly at is focused, is primarily meant to see fine detail in bright light and does not function in dim light. The cones stop working, for practical purposes, at light levels between 0.1 and 0.01 millilambert (mL.). Below this level we are dependent on the rods. It is, therefore, impossible to look directly at anything, since there are no rods in the center of the retina, and what we can see cannot be perceived in fine detail. (3) Finally, the rods have a somewhat different sensitivity to various wavelengths of light than do the cones. Specifically, they are less sensitive to, i.e., less affected by, the long (red) wavelengths.

Dark Adaptation. Dark adaptation is a process by which the eye develops an increased ability to see dimly lit objects. This process permits the eye to function through a range of light intensities of around 12 orders of magnitude; that is, the brightest light which the eye can tolerate is around 100 billion times as bright as the dimmest light which it can perceive.

The total time of dark adaptation is, for all practical purposes, around 30-45 minutes, although there may be a further small decrease in threshold with continued time in the dark up to about two hours.

During the course of dark adaptation, the point of maximum sensitivity gradually shifts away from the center of the eye to a point about 15° in the periphery. There is at the same time a sharp decline in visual acuity,¹ a shift in the sensitivity of the eye toward the shorter wavelengths, and a loss of color vision.

Visual acuity and operational requirements.

Visual acuity is the ability to discriminate fine detail. Poor acuity means that only gross features can be seen. The relation between acuity and light intensity is a straight line function for both photopic and scotopic vision, but the decrease in acuity is much sharper for the former. Scotopic acuity ranges from 0.02 to 0.10 while photopic acuity ranges from 0.20 to 1.8.^{1,2} Table I gives the relative sizes of objects which can be seen at various light levels.

If the object which can just be discriminated at 10 mL—a comfortable level of room illumination—is taken as unity, then at 0.01 mL, the lower limit of the photopic range, an object must be six times as large to be seen. At the upper limit of the scotopic

Table I. Relative target size which can be discriminated at various light levels.

	Light level (mL)	Target size
Photopic	100	½
	10	1
	1	2
	.01	6
Scotopic	.001	17
	.00001	45

range, it must be 17 times as large while around the bottom of the scotopic range it must be 45 times as large. If the light level is raised to 100 mL, an object half the size of that at 10 mL can be seen.

This decline in visual acuity with decreasing light level is the main source of difficulty for carrier operations. It is hard to reconcile the opposing demands for low light levels for

ship concealment and pilot dark adaptation with the needs of the maintenance personnel for high light levels to carry out their jobs. How hard depends, of course, on the amount of light needed for the specific task in question. Surveys of the maintenance tasks lead to the conclusion that some aspects of the work require the highest levels of visual acuity and, therefore, high levels of light intensity. Precisely how high depends on the importance of speed vs accuracy as performance criteria.³ In either event, however, it seems likely that an intensity level of 30-100 foot-Lamberts (ft-L) is needed for maximum performance.

Red Lighting. Since World War II, an attempt to reconcile the conflicting needs for high acuity and dark adaptation has involved the use of red light. This is typically obtained by filtering out all wavelengths shorter than 600 nanometers (nm) from a white light source (despite the disadvantage of losing about 90 per cent of the light energy). The effectiveness of a red lighting system for dark adaptation is specified by the cone-to-rod ratio.^{4, 5} This ratio expresses the relative efficiency of a luminous source as a stimulus for the cones divided by its efficiency as a stimulus for the rods. The currently accepted figure for the cone-to-rod ratio is 20-1.

This concept stems, of course, from the fact that the rods are less sensitive to red light than are the cones. It is thus possible to use a higher intensity of red light than of any other without increasing the amount of time needed for dark adaptation after the light is turned off.

It is important to note that even red light does not permit complete dark adaptation. If the eyes are adapted to a red light level which permits foveal vision, the time saved for subsequent dark adaptation is only about 5 minutes compared to the time it would have taken if the eyes had been adapted to a white light of equal intensity.^{6, 7} The total amount of time in either case is primarily dependent on the intensity level; the higher the level of adaptation to either red or white, the longer it will take to dark adapt when the light is turned off.

Light Adaptation. Dark adaptation is obviously a reversible process. The exposure of a dark-adapted eye to light causes its sensitivity to decrease. Although this light adaptation is much faster than dark adaptation, it is not instantaneous. This means that a dark-adapted eye which has been exposed to light will not necessarily require the full 30-45 minutes to regain complete dark adaptation. The time that will be required depends on both the intensity and duration of the light reaching the eye.⁸ If, for example, a dark-adapted eye is exposed for 5 seconds to a dim red light of about .05 mL, recovery will take about 15 seconds; 5 sec exposure to white light at this intensity will require a little over a minute. Exposure to bright room lighting for 20 seconds requires around 7 or 8 minutes for re-adaptation; exposure to red light of about 50 mL requires 5 or 6 minutes of re-adaptation. The destruction of dark adaptation for most practical purposes requires exposure to ordinary room lighting for about 5 minutes⁹ although there is evidence that complete destruction of dark adaptation may take around 20 minutes.^{8, 10}

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Section II.—Background Information for Naval Lighting Problems at Night

In this paper, the same principles, in somewhat greater detail, are applied to the problems of darkened ship.

Considerations Involving the Human Visual System. The human eye contains two, fairly separate sensing or detecting systems, the daylight or cone system and the night or rod system. Each system has its own virtues, limitations, and requirements for maximum operating efficiency. For example, the cone system is capable of resolving or discriminating extremely fine visual detail and of appreciating colors, but it becomes blind when the illumination drops below a certain level. The rod system, on the other hand, is sensitive to minute amounts of visible radiation but requires gross targets for discrimination and is incapable of perceiving differences in hue.

These differences are interesting, well-documented, and are beginning to be comprehended at the physiological level. It is, however, the requirements for maximum operating efficiency of the two systems that are of importance for shipboard lighting design since the two sets of requirements are often diametrically opposed to one another.

The Cone System. Good visual acuity, mediated almost entirely by the cone system, varies with a number of factors: of primary importance is the amount of illumination falling on and reflected from the target. This capability is measured by determining the size of the detail that can be discriminated. Since the smaller the detail, the better the acuity, the formal definition of acuity is the reciprocal of the size, in minutes of arc, that can be seen.

$$\text{Visual acuity} = \frac{1}{\text{visual angle in minutes}}$$

It has been shown repeatedly that visual acuity increases linearly with the amount of illumination on the target, measured in log units; an example of this function is shown in Fig. 1.¹

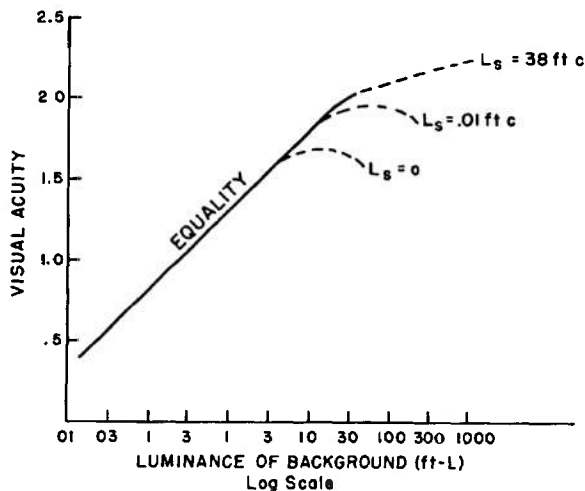


Fig. 1. The relationship between acuity and illumination. L_s refers to the light level in the interior of the booth in which the subject was tested. (Lythgoe, 1932)

Thus, it can be seen that with luminance levels of 20 to 30 ft-L and higher, target detail subtending 0.5 minutes of visual angle

($\frac{1}{0.5} = 2.0$ V.A.) can be resolved. If the

luminance drops to 0.1 ft-L, however, the detail must subtend 1.25 min., or be over twice as large, to be perceived by the same individual.

While this is a fundamental relation, a number of other variables affect the visual acuity obtainable. The type of detail to be resolved (or the type of test target) is one such variable. The data of Fig. 1 were obtained with a Landolt ring; this target is essentially a circle with a gap in it that can be rotated. The subject's task is to locate the position of the gap. Other types of visual acuity targets, as letters or checkerboard targets, are more difficult; i.e., the size of the detail needed for resolution at a given light level is larger. Some tasks, for example, locating a gap or irregularity in a line, are easier and the minimum visual angle that can be seen at a given light level

is much smaller than the value for the Landolt ring. However, no matter what the target, as long as it is constant, a curve similar to the one shown in Fig. 1 will be found as a function of illumination level. This results in a family of curves, one for each type of target, all of which show increasing visual acuity with illumination level and which are related to one another by constant factors. Thus, it is possible to transpose from one type of target to another by multiplying the visual acuity by the appropriate constant.

Figure 1 also illustrates another variable that affects performance—the fact that maximum acuity is obtained when the illumination on the surrounding area is at the same level as it is on the target. If the target is brightly lighted and the surrounding area is dark, acuity is impaired, not reaching the values obtainable with an equally-lighted surround. The investigator in this study could not, for technical reasons, obtain surround illuminations of 100 or 1000 ft-L; presumably if he had, acuity would have continued to rise in a linear fashion with illumination.

A third variable affecting visual acuity is the amount of contrast between the target and background. Figure 2 gives a sample set of data relating visual acuity to illumination

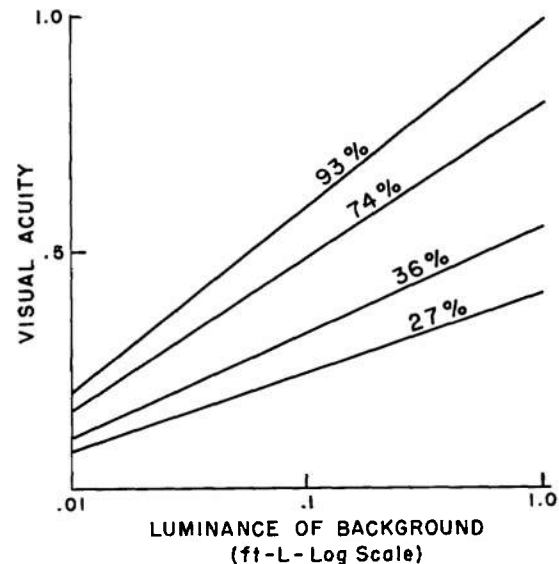


Fig. 2. Visual acuity as a function of contrast and background luminance. (Moon, 1936)

level for various contrasts.² The higher acuity levels are only reached with high contrast between target and background as black on white or vice versa. Once again families of curves are found and it is possible to transform from one contrast level to another with the appropriate constant. For example, acuities at 30% contrast (comparable to say gray on white) are approximately half of what they are for black on white at every luminance level.

The functions shown thus far are results for the emmetropic or normal eye; most subjects can be brought to this level of acuity by suitable corrections (glasses) if they need them. However, acuities for uncorrected individuals differ widely depending on their refractive error, i.e., whether they are hyperopic, myopic, or have astigmatism. Type and degree of refractive error thus provide one more variable affecting acuity as illustrated in Fig. 3.¹ Once again functional relationships are found between illumination level and acuity with families of curves that are related by constants one to another.

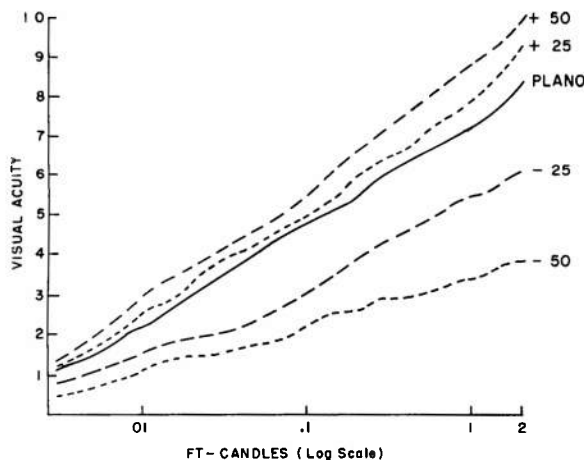


Fig. 3. Variation of acuity with illumination for groups with different types of refractive error. (Pratt and Dimmick, 1951)

While the number of variables which affect acuity is certainly large, including target/surround luminance ratio, contrast,

and the refractive error of subjects, one generalization can be made: If an individual needs to see better, or finer detail, for any reason, one way of helping him is to give him more light.

The Rod System. The most important capability of the rod system, detecting small amounts of light or seeing dimly lighted objects, is achieved only after the eye is dark adapted (i.e., has spent a considerable period of time in the dark). The length of time required depends upon a number of factors. Of major importance is the intensity of the illumination to which the individual was subjected prior to the period of darkness, with the brighter the prior exposure, the longer the time required.

Figure 4 gives some classic examples of typical dark adaptation curves following exposure to lights of different intensities.⁴ The dark adaptation curves vary greatly depending on the pre-exposure; after bright light, the rod portion of the curve is not evident for 10 minutes or more, while with low intensities, there is no cone portion, rod adaptation beginning immediately. It should be noted, however, that these extreme differences would be somewhat unusual in the operational situation. The higher intensities are common only in natural daylight and sunlight; dark adaptation following such exposures is fairly rare. The light levels from 1 to 100 mL, representative of interior lighting, would be the normal pre-exposure at night and these levels are followed by relatively rapid dark adaptation.

Similar families of curves are found as a function of exposure duration also illustrated in Fig. 4. The primary conclusion to be drawn from the large amount of data on the subject is that, the smaller the quantity of light (whether intensity or duration) to which an individual is subjected, the faster the subsequent dark adaptation.

This then is the requirement in major conflict with that for maximum visual acuity. One cannot have the light necessary to see fine detail and subsequently see at low levels without spending some time in the dark. If, on the other hand, one restricts the prior

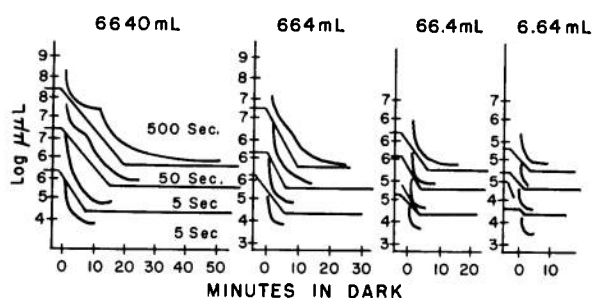
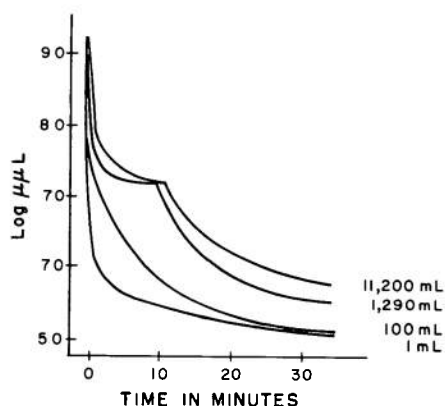


Fig. 4. Dark adaptation thresholds following exposures to various luminances: 1) for exposure durations of 5 minutes and a 7° , centrally viewed test field, (Brown, 1954) 2) for various exposure durations and a 3° test field, centered 7° in the periphery. (Mote and Riopelle, 1953)

illumination level so as to be somewhat dark-adapted, this level may be seriously inadequate for the visual tasks to be performed.

Solutions—Red lighting. In the operational situation it may not be practical to wait in the dark after performing duties within the ship before going on deck. Of the many partial solutions or compromises to the problem, red lighting is the most common, and is of general usefulness. The advantage is derived from the fact that visual acuity is as good in red illumination as it is in an equal

amount of white illumination while the time required to become dark adapted is somewhat shorter following this red light.

These facts have been demonstrated many times and have both a theoretical and empirical foundation. With regard to visual acuity, all units of light, whether illumination or luminance, are defined on the basis of the efficiency of radiant energy of different wavelengths in producing a visual response. While the visual response used in the definition is not acuity but rather light sensation, the net result is the same—for all practical purposes, equal amounts of light of different wavelengths yield equal visual responses within the photopic system. Empirical verification has been made and supports this definition.

With regard to dark adaptation, the advantage of red lighting lies in the fact that the sensitivity or efficiency curve of the rod system is shifted toward the short wavelength by about 45 millimicrons. The rod system thus is not as sensitive to the long wavelengths as is the cone system; red light which is equal photopically to white is, for the scotopic or rod system, effectively less intense than the white. It is as though one had been exposed to a lower intensity white in Fig. 4. The amount of this reduction can be calculated and is the basis of the cone-to-rod ratio—a numerical index used to assess the adequacy of red lighting installations for night vision. The ratios decrease, indicating poorer performance for night vision, as the color of the illumination is shifted from long or red to short or blue wavelengths.

Once again, there have been numerous empirical studies verifying this theoretical account as well as a number of practical studies showing the size of the advantage or the time savings realized when red is used in place of white light.

This advantage of red over white light holds also for accidental exposure to light for a dark-adapted person. The amount of damage to night vision when a dark-adapted person looks, for example, at a lighted doorway that unexpectedly is opened, at a search light or a match, depends upon the intensity

of the light and the length of time it is viewed. The red light, however, is less detrimental and can be compared, in its effects, to a white light of lower intensity. Figure 5 illustrates this for several intensities and durations of red and white light.⁵

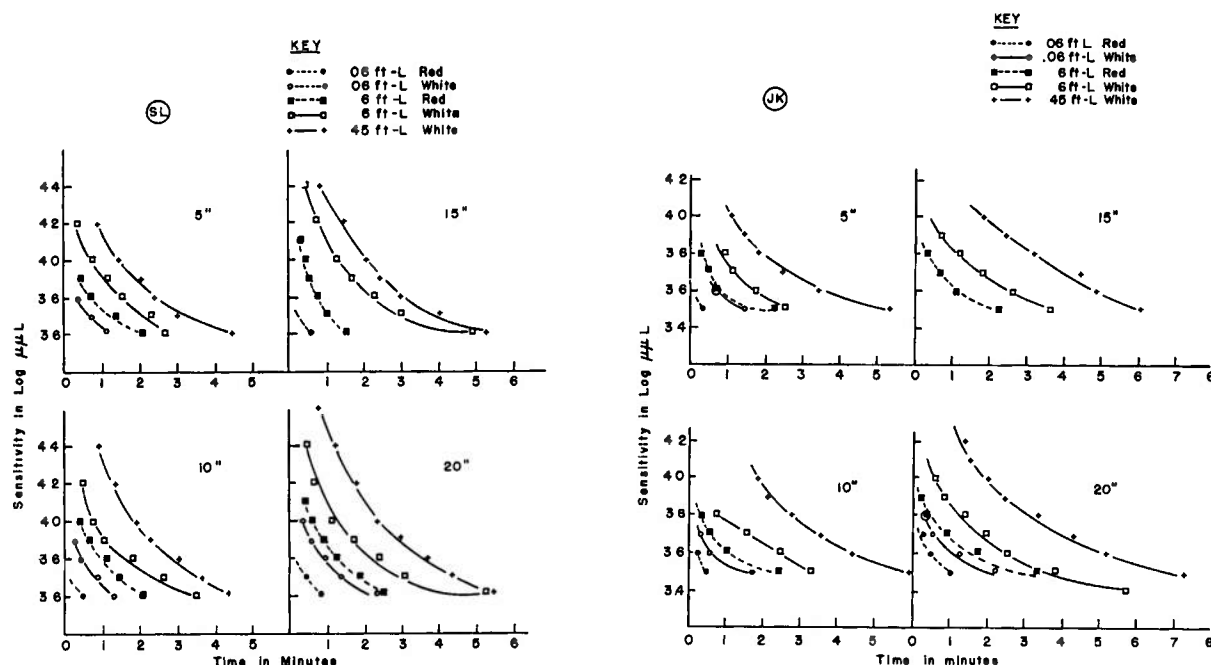


Fig. 5. The time required to readapt following four durations of exposure to various intensities of red and white light, (Luria & Kinney, 1961)

Solutions—Other. While the effectiveness of red lighting has been demonstrated on numerous occasions, it is not a panacea for all lighting problems and it is undoubtedly more widely used than it should be. If, for example, the tasks to be performed on the deck of the ship require considerable visual acuity or color discrimination, and thus utilize cone rather than rod vision, red lighting has no advantage whatsoever, and may prove to be quite a hindrance.

Similarly, if a man who needs to have dark-adapted rod vision remains in a room with a normal shipboard illumination level around 10 footcandles (ft-c), he will dark-adapt rapidly, to a useful level after 10 min-

utes or less in the dark and the savings in time of red over white light will be only two or three minutes.⁶ One obvious solution is to have the man on deck 13 minutes before he needs his dark adaptation rather than 10 minutes prior.

Extra-visual Considerations. There are a number of other factors, monetary and operational, which must be considered in assessing the optimum lighting system for any task. Several of these are listed briefly below:

- 1) The requirement for darkened ship as a Naval procedure to minimize detection must be weighed against the sophistication of the enemy's sensing devices. If the ship can be spotted, for example by radar, at far greater distances than by the human observer, then the requirement should be revised. Many night-time operations could be simplified by flood-lighting. If, however, a possibility of visual detection exists, darkened ship is, of course, a necessity.

2) The advantage of red lighting in helping conceal the ship from human lookouts is a sizable one when calculated from the point of view of a dark-adapted visual system. However, another variable in the operational situation should not be ignored—the absorption of radiation by the atmosphere. In certain situations, particularly for horizontal paths of light (for example, viewing one ship from another), the short wavelengths are absorbed by the atmosphere while the long (red) wavelengths are transmitted relatively well.⁷ Thus, some of the advantage of using a light to which the human lookout is insensitive is lost, since this red light is transmitted better than lights of other colors.

3) Red light is usually achieved by selective filtering of a white light source. Herein lies one of the criticisms of red light as an illumination system and that is that 80% of the light (and electrical power) is wasted because of the filtering effect. In spaces as large as the hangar deck of an aircraft carrier, this fact may be of some importance.

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III. Merits of Red or White Lighting for Naval Use

The advantages and disadvantages of red vs white lighting for ships at night are assessed in concrete terms.

Introduction. Low level red lighting systems are presently used at night in many shipboard areas for two reasons, first, to promote dark adaptation and, second, to minimize visual detection of the ship. Some comments on both of these aspects will be made in this paper.

Although red lighting at night apparently has rather wide acceptance as a general procedure, the relative merits of red vs white lighting should be evaluated in relation to the visual requirements in each specific condition. In the Submarine Force, for example, the situation aboard the newer submarines is fairly straightforward; dark adaptation is needed only for a periscope operator. Since only one man is involved and a number of other solutions are possible, red lighting is not good practice, both in terms of its cost and its inconvenience to other crewmen.

Aboard aircraft carriers, on the other hand, the situation is much more complex. The visual requirements of the pilots, the bridge, the maintenance men, and the hangar deck crews must all be considered; in many cases they are antagonistic and the most effective compromise must be worked out.

Each situation involves two somewhat distinct problems, (a) level of dark adaptation needed and (b) the speed of readaptation after exposure to light, whether intended or accidental.

Pilots, for example, need to be dark adapted for night take-offs and rendezvous, but they need to go through a pre-flight briefing, must check their planes before take-off, and are exposed to light from jet engines in the planes in front of them. On the way to the flight deck, they may also have to pass through airplane maintenance areas which should be well lit to permit the mechanics to do their work. The mechanics, on the

other hand, may suddenly be called to service some unexpected breakdown on the darkened flight-deck and may then need some level of dark adaptation.

Over the past few years data have been collected in this laboratory comparing the relative effects of red and white light on subsequent dark adaptation and on the speed of readaptation of both peripheral sensitivity and foveal acuity after exposure to various intensities and durations of white and red light; there follows first a discussion of the relative effects of red and white illuminants on ship detection in the light of recent data on atmospheric transmission.

The Practical Value of Red Light on Subsequent Dark Adaptation. There is no question that pre-exposure to red rather than to white light results in faster subsequent dark adaptation. Numerous studies have emphasized the statistical significance of the difference. Less attention has been paid to the absolute difference of time or sensitivity, or to such matters as the optical duration of red adaptation.

Mitchell, Morris, and Dimmick¹ showed that there is no further advantage to be gained from red adaptation after ten minutes in red. Figure 1 shows their dark adaptation curves after adaptation to 325 ft-L of white

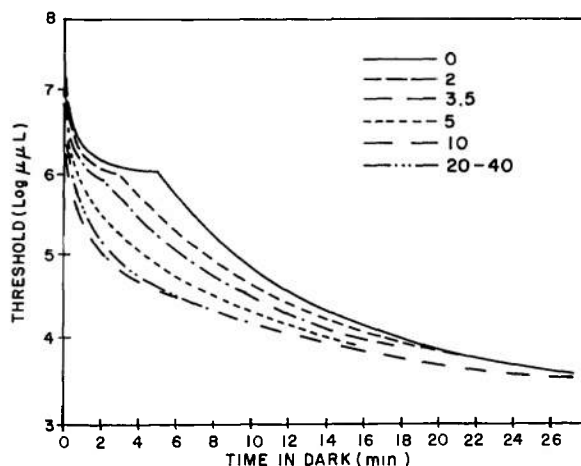


Fig. 1. Dark adaptation following different durations of red adaptation. (From Mitchell, Morris, & Dimmick, 1950)

light or to 16 ft-L of red light for various durations from 2 to 40 minutes. There is virtually no difference between the dark adaptation curves following adaptation to red light for 10 minutes or more.

Figure 2 makes this point more clearly by showing the difference between the thresholds obtained after various durations of red adaptation and that obtained after the white adaptation. It should be noted that the magnitude of the differences can be varied by changing the level of adaptation used as the base line. These differences have been greatly magnified by comparing 16 ft-L of red

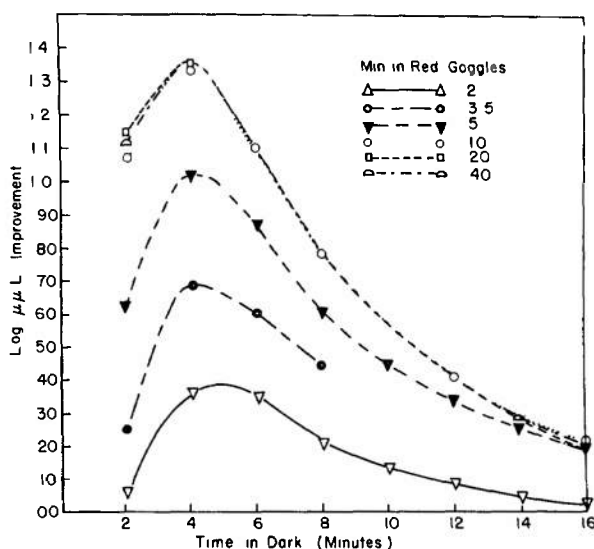


Fig. 2. Improvement in brightness threshold following different durations of red adaptation. (From Mitchell, Morris, & Dimmick, 1950)

with 325 ft-L of white, but the basic conclusion would remain unchanged: Thus, the instances of men, preparing for night watch, adapting for 30 minutes under red light is a waste of time. The assumption in such cases, of course, is that red adaptation is equivalent to dark adaptation, but it is not true. Adaptation to red light produces at best only an intermediate level of dark adaptation, as shown in Fig. 3. How close the upper curve will come to the curve for dark adaptation depends on how dim the red light is, but the dark will always be superior.

Furthermore, the advantage of red varies with the intensity level of the adapting light. Hecht and Hsia² studied the relative effects of three levels of red and white light on subsequent dark adaptation of one observer. Their results have been reanalyzed in Fig. 4 to show the gain in sensitivity of their observer resulting from the use of red light rather than white light of equal brightness. The advantage of the red obviously increases with the intensity of the adapting light. But in the practical situation, of course, the dimmest light possible is used, thus reducing its advantage to relatively small amounts.

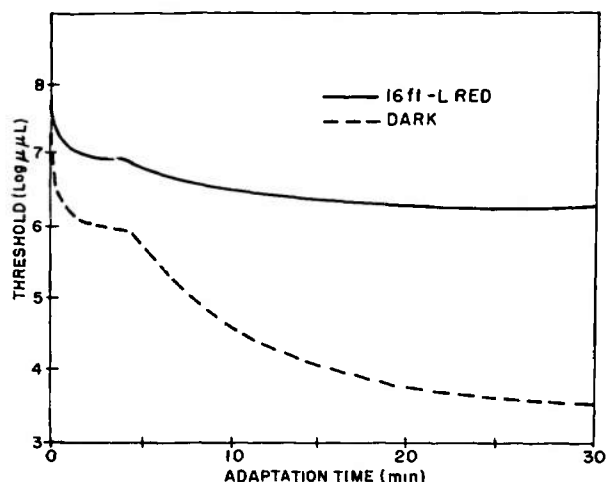


Fig. 3. Brightness sensitivity during exposure to the dark or to 16 ft-L of red light. (From Mitchell, Morris, & Dimmick, 1950)

What, then, is the saving in time effected by red over white adaptation? It is clear from every study which has been carried out that, under practical conditions, the maximum saving is around 3-5 minutes at most. Data has been collected showing the savings for both sensitivity and scotopic acuity.

Figure 5 is a reanalysis of data from Katz, Morris, and Dimmick,³ and shows the time saved in reaching various levels of sensitivity after adaptation to 16 ft-L of red rather than 16 ft-L of white. The time saved ranged from about 15 seconds for a sensitivity level of 6 log micromicrolamberts ($\mu\mu\text{L}$) to maximum saving of about 3.5

minutes for the lowest level reached after 30 minutes of dark adaptation.

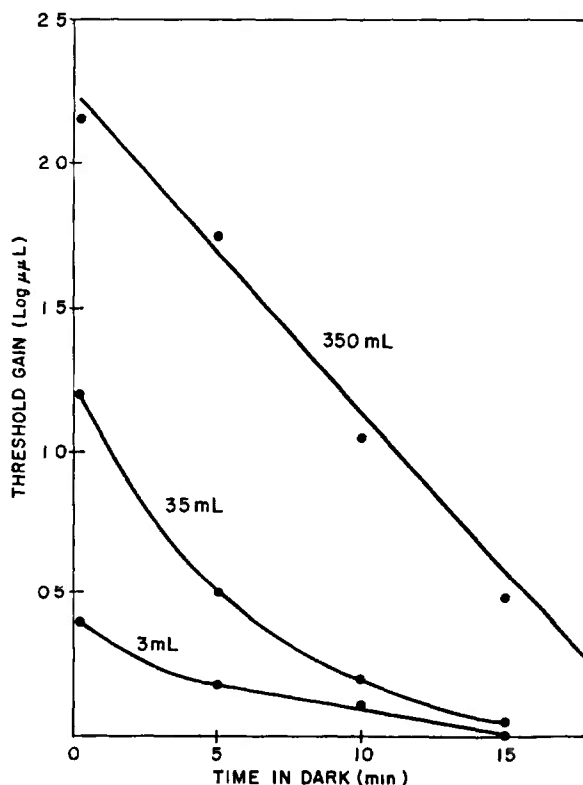


Fig. 4. Improvement in brightness threshold following exposure to various levels of red light compared to exposure to equivalent levels of white light. (From data by Hecht & Hsia, 1945)

Their data can be analyzed in yet another way to show the gain in sensitivity produced by red adaptation after various times in the dark (Fig. 6). The maximum gain occurs after one minute in the dark; it amounts to little more than .5 log $\mu\mu\text{L}$. Further time in the dark results in less and less advantage for red adaptation.

Luria and Schwartz⁴ investigated acuity rather than sensitivity. That data can be similarly reanalyzed. Figure 7 shows the time saved with red light (3.4 ft-L) in reaching various levels of acuity when the target is illuminated to different light levels. The advantage of red typically increases as acuity increases just as it did for increasing sensitivity. Further, the saving increases with

decreasing target illumination. Once again, however, the maximum saving is less than four minutes.

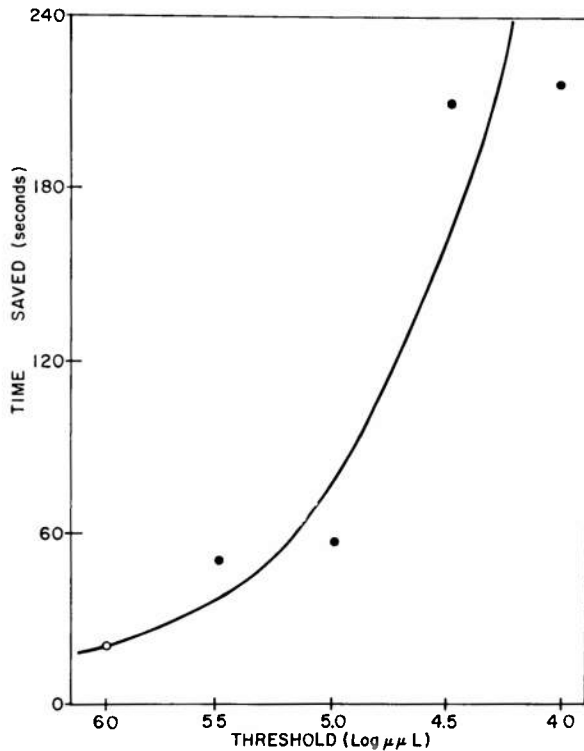


Fig. 5. Time saved in reaching various brightness thresholds by adapting to 16 ft-L or red for 10 minutes rather than to white. (From data by Katz, Morris, & Dimmick, 1954)

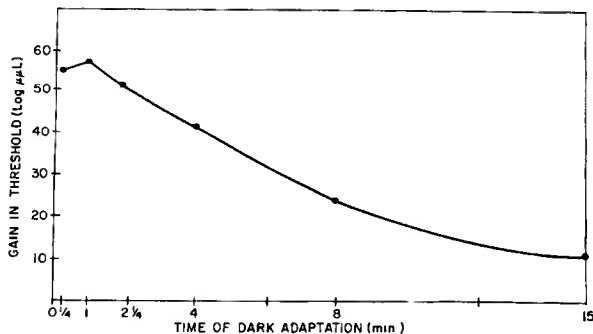


Fig. 6. Improvement in brightness threshold after 10 minutes of adaptation to 16 ft-L of red rather than white. (From data by Katz, Morris, & Dimmick, 1954)

It is hard to imagine a practical situation in which a saving in time of a few minutes would be of operational significance. If men

know in advance that they must be dark adapted, it can scarcely matter whether they spend 30 or 25 minutes adapting. And the expense and inconvenience to others of red lighting certainly does not warrant it.

It may be, however, that a periscope operator, for example, would be concerned with his acuity after looking into the periscope for a certain amount of time. Figure 8 shows the advantage of red light in terms of improved acuity for various times in the dark. As the target illumination increases, the gain decreases. But if the illumination is, for example, 4 log $\mu\mu$ L, then the added acuity is around .016. In comparison, the added acuity for an eye which has been in the dark for that period of time would be around .03, nearly twice as much. It is, in short, easy to see why many officers choose to be as nearly dark adapted as possible rather than satisfy themselves with red adaptation.

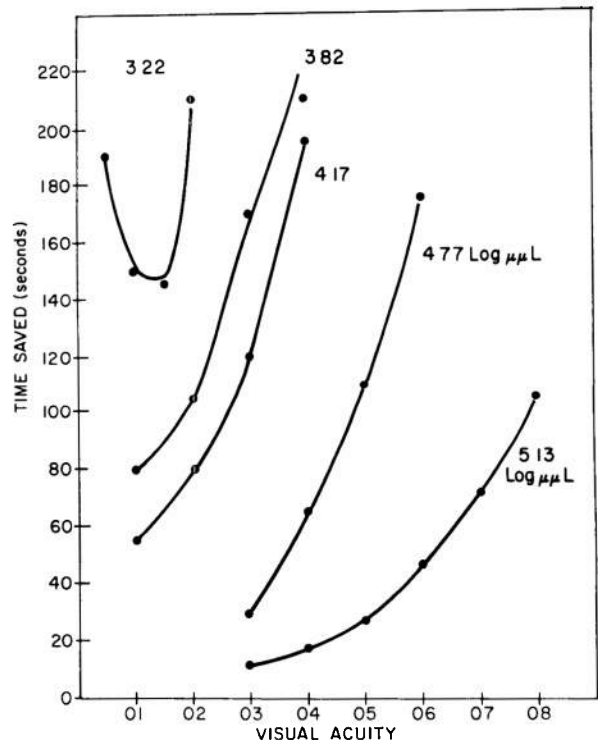


Fig. 7. Time saved in resolving various acuity targets illuminated to various intensity levels after adaptation to 3.4 ft-L of red rather than white light. (From data by Luria & Schwartz, 1960)

Recovery of Dark Adaptation. A second problem of dark adaptation concerns the time required to readapt after exposure, either intended or accidental, to light. If, for example, certain compartments on a ship are kept dark while others are lighted, what would be the effect on dark adaptation of brief exposure to the light if a door were accidentally opened? Or, what is the effect of having to turn a light on for a few seconds to look at a chart? This question is probably of more importance than the question of how long it takes to adapt in the first

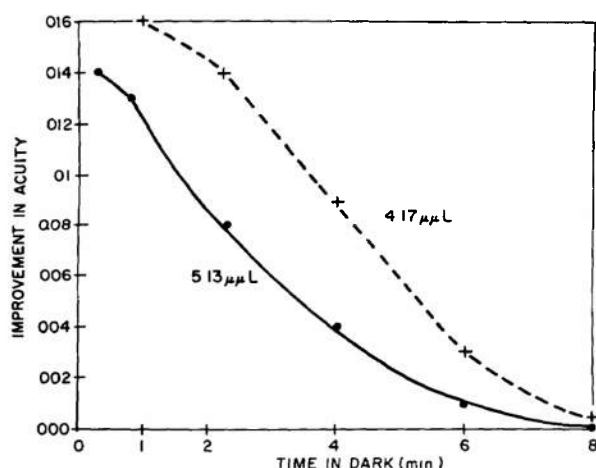


Fig. 8. Improvement in acuity for targets illuminated to either 4.17 or 5.13 log $\mu\mu\text{L}$ after adaptation to 3.4 ft-L of red rather than white light. (From data by Luria & Schwartz, 1960)

place. There are many people who believe that dark adaptation is completely destroyed by a few seconds of exposure to light.

For this reason, a comparison was made of the effects of exposure to large areas ($35 \times 45^\circ$ visual angle) of white or red light varying in intensity from .06 to 45 ft-L for durations of 5 to 20 seconds.⁵ Figure 9 shows the results for a typical observer. It will be seen first of all that readaptation even to the brightest white light (45 ft-L) exposed for 20 seconds was complete for this subject in less than six minutes, considerably less time than the original 30 minutes needed to reach this level. Changes are less after exposure

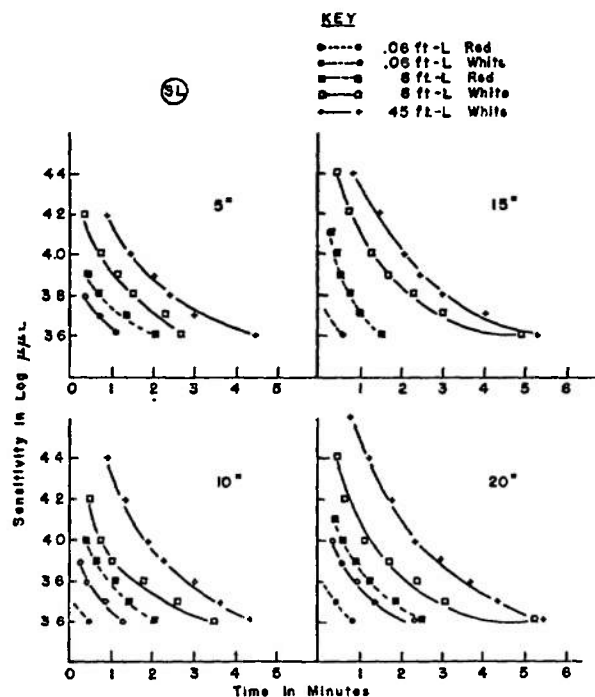


Fig. 9. Time required to readapt after four durations of exposure to various intensities of red and white light. (From Luria and Kinney, 1961)

to red than to white light and recovery is faster. Figure 10 shows the average recovery time as a function of the intensity of the light times its exposure time. For the longer values of $I \cdot t$, the saving of time for red is rather constant at around 1 minute. But for the higher values, while the slope of the red function is still unchanged, that of the white one has increased sharply. At the highest value of $I \cdot t$ plotted, the saving in time has increased to more than 2.5 minutes. It appears, thus, that the white curve (and presumably the red curve also at some point) exhibits the same increase in slope which has been carefully determined for recovery of foveal acuity by Kinney and Connors.⁶

The saving in time gained by the use of red is, thus, quite comparable to the savings during original dark adaptation. But it seems to us that these temporal periods would be of more practical importance during readapta-

tion. The value of red light is most significant when light must be used to interrupt completed dark adaptation than it is in effecting rapid dark adaptation to begin with.

Red Lighting and Concealment of Ships. Prior to the Second World War, U. S. Navy ships used blue lights at night. It appears to have been Selig Hecht⁷ who was instrumental in getting them changed to red lights. The reason advanced, of course, was that a dark-adapted enemy lookout would be far less sensitive to the red light than to the blue.

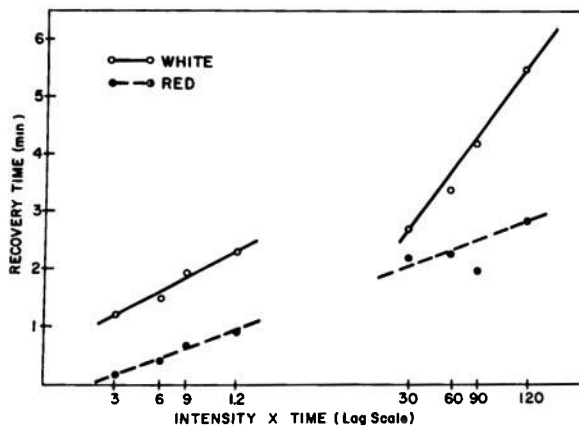


Fig. 10. Time required to readapt as a function of the intensity-duration product of white and red interrupting stimuli for one observer. (From data by Luria & Kinney, 1961)

At that time there was little information on the transmission of various wavelengths through the atmosphere. Only in the last 15 years or so has there been collected any sizable amount of data bearing on this problem. Much of it has been recently summarized by Gates.⁸

Figure 11, based on graphs presented by Gates, shows the distribution of solar energy which reaches the surface of the earth when the sun's rays are travelling at different angles from the vertical. When the light is travelling along a vertical axis, it is said to have a "slant path" of 0° . A pilot directly

over a ship would have a slant path of 0° . A lookout on another ship would have a slant path of 90° . Figure 11 shows that maximum transmission of energy along a slant path of 0° occurs at about 500 nm. As the slant path increases, the distribution of energy across the visible spectrum gradually changes until at a slant path of 83° , maximum trans-

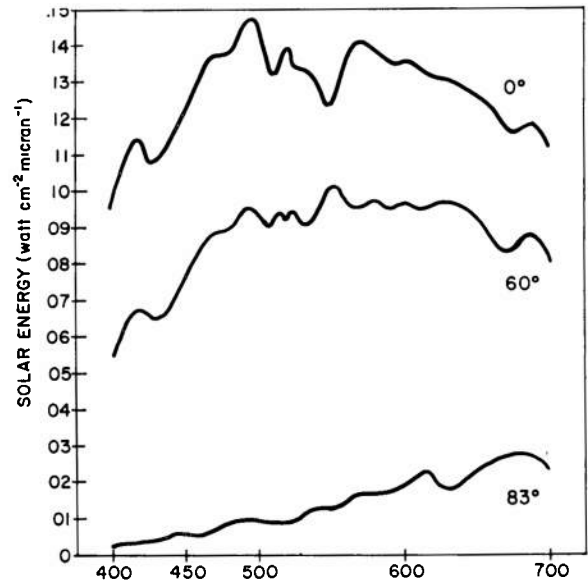


Fig. 11. Spectral distribution of direct solar radiation at sea level for various slant paths. (From Gates, 1966)

mission occurs in the red. The curve is remarkable in view of the distribution of solar energy outside the earth's atmosphere, shown in Fig. 12, which is rather deficient in the long wavelengths.

It is apparent that there is a sharp increase in the transmission of red relative to that of the blue as light passes through an increasing density of air. The amount of this increase is shown in Fig. 13 in which is plotted for each wavelength the ratio of the energy transmitted at a slant path of 0° .

Obviously, red and blue lights equated for visibility along one slant path will be equally visible along another path. The immediate question is, will the advantage for concealment which red light has when based on

measurements made in the laboratory, where atmospheric transmission is not a factor, continue to hold in the case of an enemy lookout miles away on the horizon? More specifically, will the increased transmission of red through the air offset the relative insensitivity to red of the dark-adapted eye?

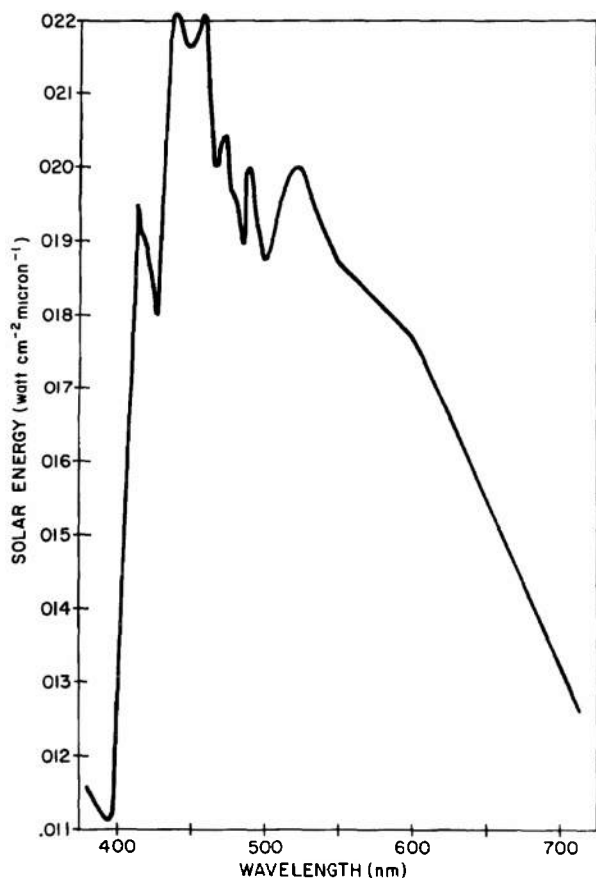


Fig. 12. Spectral distribution of extraterrestrial solar energy. (From Gates, 1966)

For practical purposes, the problem should be examined in two ways, depending on whether it is necessary to equate the red light to another light photopically or scotopically. If light of photopic intensities is needed, then the question may be asked, for example, what the relative visibilities would be to a dark-adapted observer of Illuminant A vs Illuminant A through a red plastic filter raised to the same photopic intensity. When atmospheric transmission is not considered,

then it can be shown that the "white" light is 37 times more visible than the red light to the dark-adapted observer. When both sources are transmitted through a density of atmosphere equivalent to an 83° slant path, then the advantage of the red is reduced to a factor of 19. Although the advantage has been cut in half, red still maintains a sizable advantage over the white.

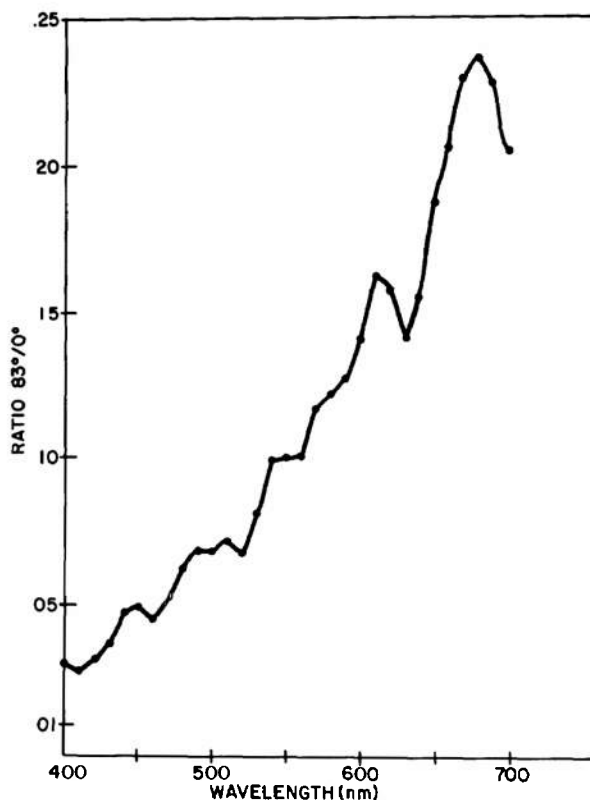


Fig. 13. Ratio of solar radiation at sea level for a slant path of 83° to that for a slant path of 0°. (From data by Gates, 1966)

There are also, however, certain situations in which only dim, exposed lights are needed on ships. Photopic intensities are unnecessary; only enough light is needed to permit dark-adapted men to move about on deck and locate certain objects. Under these conditions, the lights might be equated scotopically. If the choice must now be made between red and blue lights—equated according to the C.I.E. Scotopic Luminosity Curve—the re-

sults are quite different. The relative visibility of red and blue lights produced by two sets of filters has been calculated and is shown in Fig. 14. The solid lines show filter transmissions which give lights of equal scotopic brightness; the dotted line shows a red filter which is equal to the blue filter in both energy and scotopic brightness. Table I gives the red/blue visibility ratios for both sets of filters along three slant paths. Red is more visible than blue even along a slant path of 0° , and as the slant increases, the advantage of the blue increases. According to Gates (his Fig. 5), these computations are not affected by changes in the amount of water vapor in the air. It would seem, then, that the use of blue lights for nocturnal ship-board lighting had some basis in practical experience. Although better data are needed than seem to be currently available, the issue does not appear to be closed. The choice of color of lights which will give the best chance of escaping visual detection is probably a function of the specific situation involved.

Table I. The ratios of visibility of red to blue lights equated scotopically for various slant paths.

	Slant Path		
	0°	60°	83°
Equal Brightness	4.7	5.7	27.0
Equal Energy and Equal Brightness	1.3	1.5	6.0

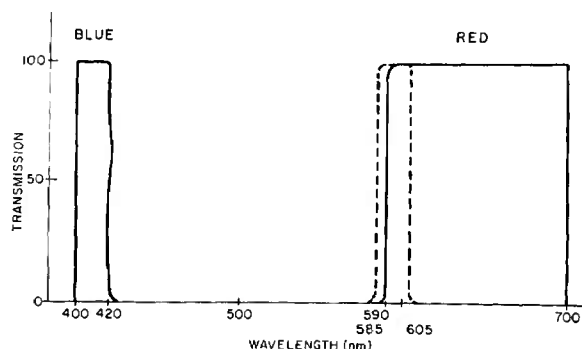


Fig. 14. Hypothetical filters which give equal scotopic brightness (solid lines) or equal energy and equal scotopic brightness (broken line).

1. Mitchell, R. T., Morris, A., and Dimmick, F. L., NavMedResLab, Naval Submarine Base, Groton, Conn., Rep. No. 166, Dec 1950.
2. Hecht, S., and Hsia, Y., J. Opt. Soc. Am. 35, 261-267, 1945.
3. Katz, M. A., Morris, A., and Dimmick, F. L., NavMedResLab, Naval Submarine Base, Groton, Conn., Rep. No. 246, Apr 1954.
4. Luria, S. M., and Schwartz, I., NavMedResLab., Naval Submarine Base, Groton, Conn., Rep. No. 343, Dec 1960.
5. Luria, S. M., and Kinney, Jo Ann S., NavMed ResLab., Naval Submarine Base, Groton, Conn., Rep. No. 347, Feb 1961.
6. Kinney, Jo Ann S., and Connors, Mary M., Nav SubMedCen., Naval Submarine Base, Groton, Conn., Rep. No. 464, Dec 1965.
7. Anon., Sci. Amer., 169 (7), 1942 p. 25.
8. Gates, D. M., Science, 151 (3710) 4 Feb 1966, 523-529.

IV. Comments on the Effect of Orange vs Red Pre-adaptation.

The specific question as to the effect on night vision of using yellow or orange rather than red lighting is answered by calculating the effect on the human scotopic (night vision) system.

The superiority of the orange/red lighting reported by the Pacific Fleet when they painted light bulbs with orange paint instead of using standard Navy red filters, undoubtedly stems from the increased illumination levels possible using this procedure. Up to eight times as much light is available with yellowish-orange filters as with standard Navy red. Needless to say the men liked it better—they could see so much better.

The effect on dark-adaptation is twofold: interference due (1) to the overall increase in illumination and (2) to the shorter wavelengths employed in "orange" light.

One can, of course, equate the intensity levels of orange and red light to compare for differences specifically due to wavelength; this is the usual experimental procedure. It is also possible to calculate the effects for equal luminance sources. The steps are as follows:

1. For any desired energy distributions, determine the relative energy required at each wavelength (E_λ) in order that the product of the energy times the photopic luminosity curve (V_λ) [$\sum E_\lambda V_\lambda$] equals 1.0.

2. Determine the relative scotopic luminances for the same energy distributions by multiplying the spectral energies by the scotopic luminosity curve ($V_{\lambda_{sc}}$). The product [$\sum E_\lambda V_{\lambda_{sc}}$] represents the effectiveness of this distribution of energy as a stimulus to the scotopic system.

3. Since the scotopic luminances thus calculated are all relative, take the ratio to some standard to determine relative effectiveness. The generally accepted standard is a source of 2042°K.

A number of these calculations have been made in the past;^{1,2} similar calculations in Table I have been performed for this particular problem.

Table I. Calculation of Scotopic Effects

Energy Distribution	Relative Photopic Luminance	Relative Scotopic Luminance	Ratio
Standard Navy Red (cutoff=600 mμ)	1.0	.016	.04
Yellow Wratten #12 (cutoff=500mμ)	1.0	.391	.96
2042°K	1.0	.376	1.0
6486°K	1.0	.983	2.5

Interpretation

1. A source of 6486°K is 2.5 times as bright, to the scotopic system, as the low color temperature standard of 2042°K, when the two sources are equated photopically. Thus, a light of 2042°K could be 2.5 times brighter photopically as Illuminant C and have the same effect in terms of bleaching the scotopic system.

2. The yellow Wratten filter is essentially the same as the 2042°K source

3. Standard Navy red, equated photopically to 2042°K, is 1/24th as bright as 2042°K to the scotopic system. The Navy red could thus be 24 times as intense and be the equivalent scotopically to 2042°K.

These results show the major advantage, as far as dark adaptation with long wavelength sources is concerned, is completely lost for yellowish light.

There are, of course, engineering advantages with the greater light output of yellow or orange filters. However, since dark-adaptation curves following yellow and orange are very similar to those following low color temperature white, one might as well use low color temperature tungsten sources and eliminate all filters.

Once again the most important question is whether the men need to be dark-adapted or not.

V. Comments on Lighting Specification for Fork Lifts Used on Supply Ships.

The specific question is answered as to whether or not the lighting specification for fork-lift operators on the decks of supply ships is adequate. Both the literature on ci-

1. Kinney, Jo Ann S., J. Opt. Soc. Am., 46, 1093, 1956.

2. Kinney, Jo Ann S., Applied Optics, 6(9), 1473-1477, 1967.

vilian night-driving and empirical determinations of visual abilities are utilized in answering the question.

The specifications for general lighting in the area in which fork-lifts operate on supply ships is reported to be .5 to 2.0 ft-c of red illumination. This light level is in the mesopic region, and considerable work has been done in this laboratory on what level of visual ability can be expected under these conditions.

The specifications in terms of ft-candles is, of course, rather meaningless since the effective luminance will depend completely on the reflectances of the surfaces. However, making the arbitrary assumption that the paint used on deck is a medium gray of 15% reflectance, we arrive at the range of .075 to .3 ft-L for the specification. This is right in the middle of civilian night-driving range of luminances and there are numerous pertinent data.

The range is shown pictorially in Fig. 1 and some comments on what is to be expected are listed below:

1. This level of vision is primarily photopic: foveal vision can be employed and undoubtedly will be since it is much easier to look directly at something one wishes to see than to use peripheral vision.

2. Color vision will be slightly poorer than at brighter levels but all colors can still be distinguished.

3. Foveal vision can be utilized effectively almost down to .001 ft-L after 5 minutes of dark-adaptation. Complete foveal dark-adaptation following these levels (.075 to .3 ft-L) takes no measurable amount of time (less than 5 sec.).

4. Peripheral dark-adaptation after these levels (have actual curves for .64 ft-L red) should be complete in 6-8 minutes. Readaptation after being dark-adapted and exposed to 20 sec. flash of such red illuminant would take 1 to 3 min. (1 min. for .06 ft-L, 3 for 6 ft-L.)

5. Targets of approximately 4 minutes of visual angle can be resolved foveally at .01 ft-L. This can be extended to predict 2 minute resolution at .1 ft-L.

6. At .0009 ft-L, most individuals find they can see as well, or better, using peripheral rather than foveal vision. Therefore, it should be assumed that .001 ft-L is the likely lower limit for foveal vision.

Thus, certainly no problem is anticipated for the fork-lift operators, if these levels of general illumination are maintained.

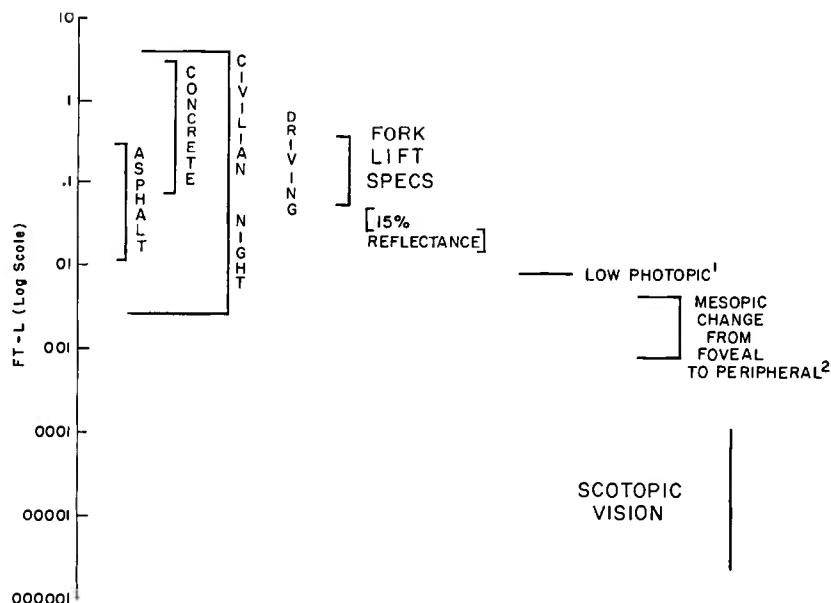


Fig. 1. Schematic display of the relation between visual tasks and illumination level.

1. Kinney, Jo Ann S., and Connors, Mary M.. Highway Research Record No. 70. Highway Research Board, National Academy of Science-National Research Council, Washington, D. C., 1965, pp 35-40.

2. Kinney, Jo Ann S., Clinical Measurements of Night Vision, in Milton A. Whitcomb and William Benson (Ed.), The Measurement of Visual Function. Washington: Natl Acad. Sci-Natl Res. Council, 1968, pp 139-152.

VI. Summary of Results at Patuxent Naval Air Station.

A field study of mechanics' performance in repairing planes under three different conditions of illumination was conducted by members of NSRDC at the Patuxent Naval Air Station. The three illuminations were .08 ft-c of red light, 5 ft-c of red light, and 5 ft-c of white light. The performance measure was the time required to complete various tasks, such as removing a tail pipe and installing a new one. Members of NSMC helped with the experimental design, observed the experiment in progress, and made the following summary and interpretation of the data.

Figures 1 and 2 show the effects of each of the three variables, all on the same scale, so the sizes of differences can be compared. Both graphs are very similar; one is for the average time for all tasks; and in the other, the average time for tail pipe exchange has been calculated to facilitate comparison with the 4th and 5th trials using the aids.

(1) .08 ft-c of red causes considerable longer working times (40 to 50% greater) than the higher illumination levels. 5 ft-c of white and 5 ft-c of red, on the other hand, result in the same temporal requirements.

(2) There is some difference among teams in total time required to perform the tasks but the difference is small. In Fig. 1 the most experienced team required the least time and the least experienced, the most, which is, of course, in the expected direction. In Fig. 2, however, where the data from the fourth and fifth trials are included, these differences have disappeared suggesting that differences in experience were overcome with sufficient practice in these tasks.

(3) There is a sizable practice effect, mainly in evidence between the first and sec-

ond trials; the effect appears to be about over at the third trial.

(4) The use of the lighting aids with ambient illumination of either .08 ft-c red or 5 ft-c red results in working times of the same order of magnitude. There is considerable savings beyond the original times required; the savings is greater of course for the .08 ft-c red level since the working time was longer at this level. The working times with the aids are also considerably below what would be predicted from the practice effect, pictured in the right hand portion of the figure. Times on the fourth trial, with one to two whole days intervening between it and the first three, would be either the same (asymptotic level) or above (poorer) than the third trial. Times with the aids, however, are considerably below the asymptotic level.

There is, of course, no statistical test which can be meaningfully used with only three data points. The data are, however, completely logical and show considerable internal consistency. There is little doubt that they are reliable and meaningful.

In addition to the time required to complete these tasks under the various light levels, there is additional data available on the state of the men's adaptation (night vision) after working in each of these levels. For practical purposes, what the visual condition of the men would be if they found themselves immediately in an environment illuminated to 4.5 log μL has been analyzed. Such a level is comparable to a partly cloudy night and is fairly representative of low level night-time conditions.

(1) After .08 ft-c of Red—Men can see the general illumination immediately, can discriminate all large targets and generally function effectively. In less than a minute they can perceive small targets near their threshold for this light level.

(2) After 5 ft-c of Red—Within 30 to 45 seconds, the men can see the general illumination and large targets. It takes about 2½ minutes before dark adaptation has reached levels required for small-sized targets.

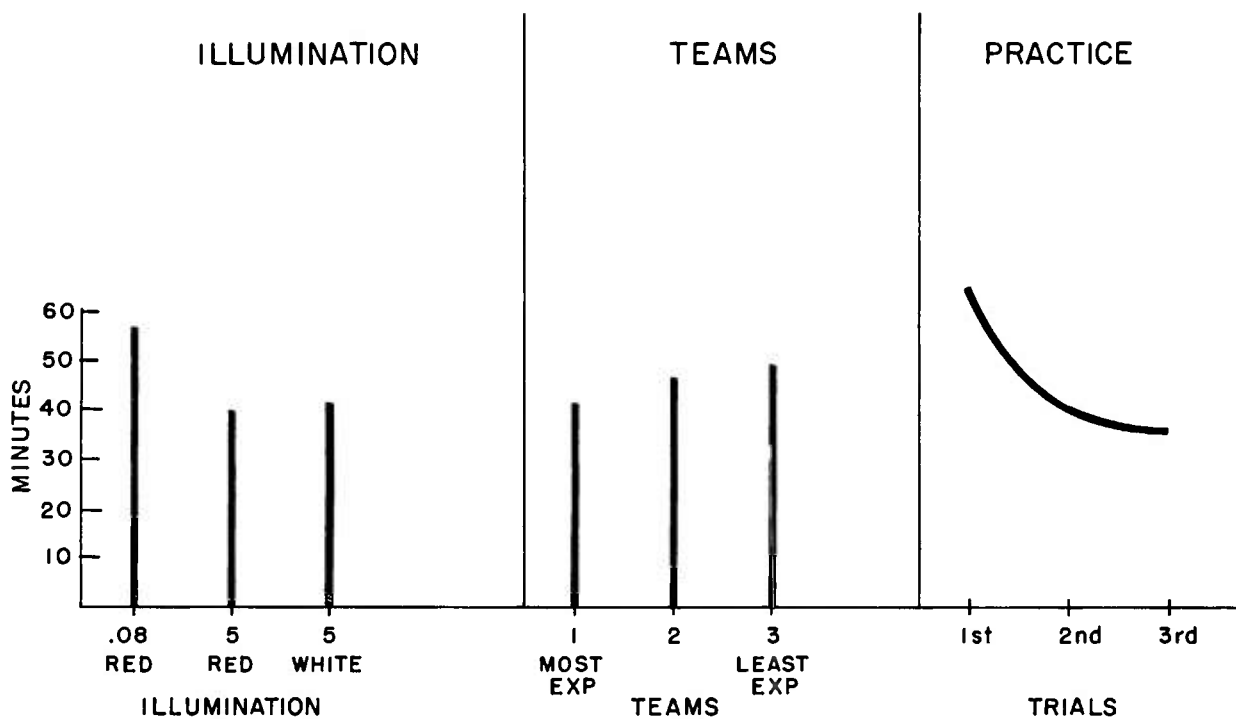


Fig. 1. Total time for all tasks (averages).

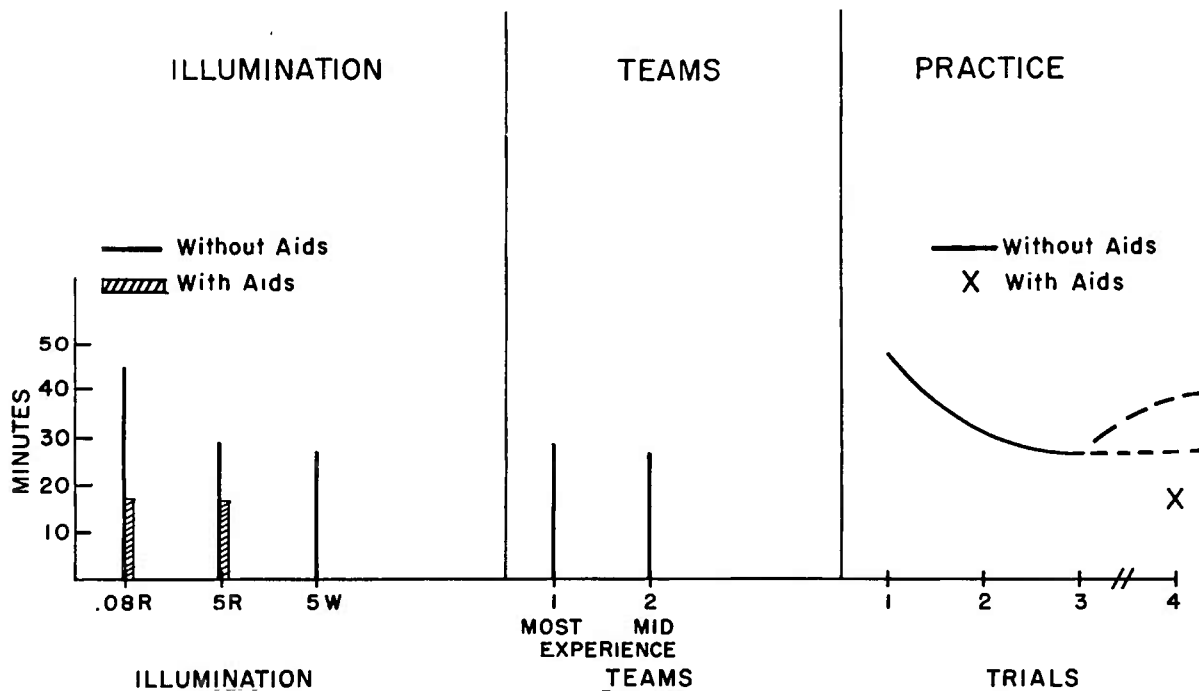


Fig. 2 Total time for tailpipe removal and installation (averages).

(3) After 5 ft-c of White—It takes approximately four minutes for men to see the general illumination or very large targets.

Until this time, the man is essentially blind; a target, no matter how large (for example, a person 3 ft away) cannot be seen. After

dark-adaptation has proceeded sufficiently so that the general illumination can be sensed, the man can avoid large objects and move about adequately. It takes another two to three minutes for him to be able to perceive small targets near threshold for this light level.

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13 ABSTRACT <p>Six papers representing analyses of a number of lighting problems encountered in Naval night-time operations are compiled in this report. These papers include general summaries of the visual factors involved and applications of these principles to specific operational situations such as the lighting of aircraft hangar decks, of underwater replenishment at sea, and of fork-lift operations.</p>			

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Night Vision						
Dark Adaptation						
Lighting Systems						
UNREP						
Hangar Deck Lighting						
Red Lighting						